CONF-750928--1

ADVANCED NUCLEAR REACTORS

D. B. Trauger
Holifield National Laboratory*
(Formerly Oak Ridge National Laboratory)
Oak Ridge, Tenn. 37830

Advanced nuclear reactors are assumed to be those not yet in service commercially. Included in this discussion, therefore, are the High Temperature Gas-Cooled Reactor (HTGR), the Steam Generating Heavy Water Reactor (SGHWR), the Light Water Breeder Reactor (LWBR), the Liquid Metal Fast Breeder Reactor (LMFBR), the Gas-Cooled Fast Breeder Reactor (GCFBR), and the Molten Salt Breeder Reactor (MSBR). The light water, magnox, and heavy water CANDU reactors are not included. The British AGR, now coming into service, appears to have a limited role. The HTGR and SGHWR, now being introduced commercially, may become early market place reactors. Efforts by governments for introducing the LMFBR have now reached the prototype stage, but much work remains to achieve commercial status. The other systems listed are perhaps more speculative, but each deserves some attention.

In most nuclear power programs much attention has been given to reactors and fuel performance, but fuel recycle is not as well advanced. Now it seems necessary for the nuclear programs to give greater attention to fuel recycle development. Even for LWR's, which are widely used, experience with recycling of plutonium to more fully utilize fuel resources has been limited. Since fuel recycle is much more important to most advanced reactors than it is to LWR's, the status of recycle technology for these systems must be emphasized.

---

*Operated by Union Carbide Corporation under contract with U. S. Energy Research and Development Administration.

The experience from both experimental and demonstration units will be reviewed. The table shows the status in summary. In general, the performance of these reactor experiments has been favorable. Most of the prototypes have experienced startup problems, but have performed well. The French LMFBR prototype Phenix has operated well from the start and now is in its second year. Although no direct experience exists for the helium-cooled GCFBR, its components are similar to those for the HTGR, and its fuel design is like that for the LMFBR. Thus it is expected to require less development than will those systems which must stand alone. The LWBR is based on LWR operating experience. The Shippingport reactor experiment is designed to assess the LWBR capability for breeding as well as demonstrate translation of technology. Recent decisions in the U.K. have led to adoption of the SGHWR for the next several commercial units there. Although of the pressure tube design, it draws heavily on LWR technology and on CANDU experience with heavy water.

HTGR experience is becoming extensive. The Dragon and the German AVR experimental reactors continue to operate well after nine and eight years, respectively. The Peach Bottom reactor in the U.S. was shut down permanently at the expiration of its second core after operating for seven years. The cumulative and aggregate availability for these reactors has been about 90%, excluding down time for testing, changing or altering experiments, and extended maintenance periods. Even with no adjustments, they have averaged about 70%. Construction of the Fort St. Vrain 330-MWe prototype has been completed, and it is on an approach to power program. Orders for six HTGR commercial units of 750 MWe and 1160 MWe have been placed by utility companies.

Much interest has been generated in the HTGR for process heat application. In the U.S. and Europe, approximately 40% of the energy consumed is for industrial uses. Energy transport studies are of vital importance to nuclear process heat application since economical sizes for nuclear units are larger than individual user requirements. Thus it would be necessary to cluster several industrial units around a multiple reactor station in order to match power demand to an adequately reliable source. Process heat studies in Germany have concentrated on methods for transporting energy from a reactor to the user. Chemical "heat pipes" employing thermochemical reactions to provide more effective heat transfer appear attractive. The HTGR can produce gas temperatures appropriate to drive the chemical reactions.

A gas turbine HTGR coupled with a low temperature bottoming cycle offers attractive thermal efficiencies (greater than 50%) where cooling water is available. The Brayton cycle HTGR also couples effectively with dry cooling towers.

The major emphasis for advanced reactors remains with the LMFBR. Prototype units have now operated in Russia, France, and the United Kingdom. Smaller experimental units also have been tested in these countries and in the U.S., and are under construction in Germany and Japan. French and British designs have been developed for nominal 1000-MWe-size plants and the U.S. is studying a commercial-size reference design. The Russian BN-600 (600 MWe) is under construction and scheduled for criticality in 1976. This cumulative experience, together with extensive R&D and component testing, give assurance that the LMFBR can be employed for large-scale power production. Questions remain concerning the capital cost for commercial-size units when safety and environmental requirements have been met.

Development of a LMFBR industry is highly dependent on a successful and economical fuel cycle. It is necessary to breed and recover plutonium from the spent fuel in order to deploy fast reactors. Unfortunately, fuel cycle technology lags behind that for the reactors. Since the basic PUREX process of solvent extraction used for LWR fuel cycle can be employed for the LMFBR, it was earlier assumed that little development would be required. However, closer examination of the LWR experience and of the properties of LMFBR fuel shows that much development is needed for the LMFBR.

Important differences between LMFBR and LWR fuels strongly affect the head-end and reprocessing equipment design. The LMFBR has a larger ratio of cladding to fuel, the stainless-steel cladding becomes embrittled at the core center and is ductile at the extremities, and the higher burnups produce more fission products with higher decay energy and introduce new chemical problems. Plutonium solubility in nitric acid is below that of uranium, possibly requiring an additional dissolution step. The presence of sodium coolant either adhering to the fuel assembly or having penetrated a defective fuel pin also complicates the head-end processes. This may necessitate an oxidation step prior to dissolution since sodium can react violently with nitric acid. The higher levels of fission products in LMFBR fuels and increasingly stringent restrictions on release of radioactive materials to the environment may dictate new containment systems for reprocessing plants with a more complete recycle control of all steps in reprocessing and refabrication and close inventory accounting for input and output. Thus, the development of fuel recycle for fast breeder reactors can be expected to require extensive development and testing on a pilot-plant scale.

The HTGR requires a fuel recycle development program which is important because of the higher value for bred ^{233}U in this reactor. Also, the head-end and refabrication processes are unique to the HTGR fuel. The preferred practice is to burn the carbonoceous structural materials exposing the fuel for introduction to the THOREX process. Spent particles of ^{235}U and bred ^{233}U particles are desirably separated before being dissolved. After ^{233}U has been recovered it must be placed into new fuel elements. The gamma activity of the ^{232}U component necessitates coating of fuel particles, fabrication of sticks, and assembly of refabricated fuel elements remotely in facilities now being designed. This too requires demonstration on a pilot-plant scale.

The molten salt breeder reactor design has recognized the fuel recycle problem from its inception. An important feature is close coupling of the reprocessing unit to the reactor. In the MSR, a salt, Li-Be-UF_4, liquid at elevated temperature serves both as fuel and heat transfer fluid. Solid blocks of graphite arranged in a vessel of Hastelloy-N serve as a moderator and container for the fuel. Channels are appropriately provided between the blocks in the reactor core region to allow criticality and production of fission energy. The heated fuel is pumped from the core to an intermediate heat exchanger where heat energy is transferred to a secondary heat exchanger and thence to a steam generator. A side stream of primary circuit fuel salt is directed to a repro-

Protactinium is removed by extraction and allowed to decay to ^{233}U before return to the reactor. Fission products also are removed. The reactor has a low breeding ratio, but has a relatively low fuel inventory and can achieve an inventory doubling time of approximately 20 years. Developmental problems include validation of structural materials which are compatible with the fuel salt and fission products and demonstration of the fuel reprocessing cycle. The concept is of interest to avoid shipping of fuel, for safety considerations, and potentially for its economics.

Although the LMFBR is now the leading advanced reactor in development effort and should remain in that position, other reactors offer either near- or long-term advantages which also create interest at this time. The fuel cycle remains as the principal area of developmental need for most advanced systems. It is gratifying to note that the fuel reprocessing is now receiving increased attention.

Advanced Reactor Experience

Reactor Type	Experiments	Demonstration Plants	Comments
LWBR	0	0	Derives experience from LWR; Shippingport being converted to LWBR.
SGHWHR	0	2	Demonstration units in U.K. and Canada; U.K. commercial units planned.
HTGR	3	1	Also Pebble Bed THTR under construction.
GCFBR	0	0	Derives experience from HTGR system and LMFBR fuel.
LMFBR	8	3	Also several very small experiments.
MSBR	0	0	One non-breeder reactor experiment, MSR, operated four years.